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Biofuels and Vertical Price Transmission: The Case of the U.S. Corn, Ethanol, and Food Markets *

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Abstract

This is the first paper to analyze the impact of biofuels on the price transmission along the food chain. We analyze the U.S. corn sector and its vertical links with food and ethanol (energy) markets. We find that biofuels affect the price transmission elasticity in the food chain compared to a no biofuel production situation but the effect depends on the source of the market shock and the policy regime: the price transmission elasticity declines under a binding blender's tax credit and a food market shock. Our results also indicate that the response of corn and food prices to shocks in the corn and/or food markets is lower in the presence of biofuels. Finally, the sensitivity analyses indicate that our results are robust to different assumptions about the model parameters.

Key words: price transmission, food chain, biofuels, prices

JEL classification: Q11, Q21

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1. Introduction

A renewed interest in the issue of price transmission among researchers and policy makers stems from two sources. First, the recent structural changes in food and retail sectors have led to higher concentration of these sectors. Second, the global agricultural commodity and energy prices have surged recently, increasing not only the price levels but also volatility. The pass-through of the price shocks from world to domestic markets and from agricultural commodities to food prices can have significant income distributional and welfare implications. Especially, poor consumers are adversely affected by the rise in food prices and farmers' real incomes depend heavily on commodity prices; this makes the issue of price transmission very relevant from the political economy perspective.

The transmission of changes from commodity to food prices and *vice versa* varies by commodity, the time span considered, and country. These factors have been well documented in the rich literature on the topic (e.g., Gardner 1975; Reagan and Weitzman 1982; Kinnucan and Forker 1987; Ball and Mankiw 1994; McCorriston et al. 1998; von Cramon-Taubadel 1998, Azzam 1999; Gohin and Guyomard 2000; McCorriston et al. 2001; Lloyd et al. 2006; Nakajima, 2011; Rezitis and Reziti 2011; Rajcaniova and Pokrivcak 2013). The general finding of the literature is that changes in the relative prices in one market are transmitted to other markets in the agri-food chain through input-output linkages between vertically integrated up- and downstream industries.

Structural models of price transmission between the farm and the retail sector date back to the seminal paper by Gardner (1975) who derived price transition elasticities under the assumption of perfect competition in the food industry. This pioneering work was followed by

McCorriston et al. (1998) who incorporated oligopolistic competition in the food industry into Gardner (1975)'s model. They showed that the degree of price transmission from producer to consumer prices is reduced (smaller pass-through of a change in the producer price to the consumer price) when the food sector enjoys market power. In their model, under quite general conditions, consumers do not fully benefit from the decrease in producer prices when the food sector is not perfectly competitive, meaning that the food sector uses its power to lower the degree of price transmission to its own benefit. On the backdrop of the BSE food scare in the UK, Lloyd et al (2006) studied how retailers' market power affects the price transmission. They conclude that the market power of retailers prevented full pass-through of the decline in the producer price of beef, caused by food scare, to consumers.

McCorriston et al. (2001), however, show that in addition to market power, the economies of scale affect the magnitude of the price transmission elasticity. Under plausible conditions, economies of scale can offset the impact of market power and lead to even higher price transmission than under the perfect competition; thus when the price decreases, consumers can benefit more relative to perfect competition.

Despite the numerous studies on the issue of price transmission in the agri-food supply chain, we are not aware of any that would analyze either theoretically or empirically the impact of the recent phenomenon of biofuels on the price transmission. This topic appears to be of high importance given the significant impact biofuels' expansion on the world agricultural commodity markets (e.g., de Gorter and Just 2008, 2009a; Ciaian and Kancs 2011; Drabik 2011; Serra et al. 2011; Yano et al. 2010; Zilberman et al., 2013; de Gorter et al. 2013). In the period 2000 – 2010, world biofuel production increased almost six-fold[1] and a significant share of corn, sugar cane and oilseeds production is used to produce fuel rather than food. Several studies have shown that

[1] http://www.earth-policy.org/data_center/C26

the surge in biofuel production is the major cause of the recent spikes in the global grains and oilseed prices and that a strong and direct link between energy and commodity prices has been created (e.g., Wright 2011; Mallory et al. 2012; de Gorter et al. 2013).

In this paper, we ask and provide an answer to a simple question: Has the introduction of biofuels (corn ethanol) change the price transmission between the agricultural commodity (corn) and food markets? We analyze the U.S. corn sector and its vertical links to food and ethanol markets. We consider the following biofuel policy regimes: (1) a binding blend mandate (with or without a tax credit), (2) a binding blender's tax credit, and (3) no biofuel policy (but positive biofuel production). These three policy regimes are compared to our benchmark which is no biofuel production. The blend mandate and blender's tax credit are the most relevant policies used in the United States, and other countries alike, to support biofuel production. Although biofuel production has been stimulated by heavy government support, under certain conditions it can also occur without biofuel policies; therefore no biofuel policy is the third policy regime evaluated in this paper. The price transmission between agricultural and food prices is evaluated for exogenous shocks in: (1) domestic corn supply, (2) corn exports, and (3) domestic demand for food.

In the rest of the paper, we first theoretically derive price transmission elasticities for each policy regime and an exogenous market shock. To that end, we build a tractable partial equilibrium model where corn is used to produce food (and feed) and ethanol; corn is also exported abroad. As in Gardner (1975), we consider a competitive food industry, but we do not explicitly include marketing services into production function of food.[2] We focus on the impact of biofuels on the price transmission rather than on the impact of the substitution of food for

[2] Including additional variable into the food production function would complicate the exposition without providing additional insights.

marketing services on price transmission. The corn market is vertically linked to a food industry that produces final goods for consumers. The retail sector is not considered in our paper. When ethanol production is introduced, corn prices become linked to ethanol prices through a zero profit condition as in de Gorter and Just (2008), Drabik (2011), and Mallory et al (2012).

Next, we calibrate the theoretical model to the U.S. data for 2009 to quantify the price transmission elasticities. Finally, in order to identify the robustness of the results, we vary the key model parameters using Monte Carlo simulations with 5000 random draws from parameters' intervals.

We find that biofuels indeed affect the price transmission elasticity in the food chain, but only in some shock- and regime-specific conditions. More precisely, if the exogenous market shock stems in the corn market, then the price transmission elasticity does not depend on the policy regime and is equal to the transmission elasticity under no biofuel production. However, if the shock comes from the food market, then the transmission elasticity declines relative to no biofuel production scenario when the blender's tax credit determines the ethanol price, but there is no difference under a binding mandate. We explain in the paper that these differences originate in different effects of a biofuel policies on price formation. Our results also indicate that the response of corn and food prices to shocks in the corn and/or food markets is lower in the presence of biofuels.

The remainder of the paper is organized as follows. In the next section, we develop a theoretical partial equilibrium model capturing all relevant features of the corn, fuel and energy markets, and we derive formulas for price transmission elasticities for individual market shocks and policy regimes. Section 3 describes the data and the calibration procedure used. In Section 4, we present our results based on the central estimates of the Monte Carlo simulations. The last section provides some concluding remarks.

2. Theoretical Model

We develop an analytical model for the corn sector and its vertical linkages with food and ethanol markets to analyze price transmission elasticities under several settings. In order to better identify the direct impact of biofuels on the price transmission along the food chain, we abstract from modeling the linkages of the fuel market with the food sector (e.g., through higher transportation costs) and with the corn sector in the form of changing input costs for corn production.

In our benchmark scenario, entitled *no biofuel*, corn and ethanol markets are delinked and only the corn-food market chain is considered. The food market is represented by a competitive processing sector which buys and processes corn and sells corn-based food to final consumers. We then analyze how the benchmark price transmission elasticity is affected by biofuel production which creates a direct link between corn and ethanol prices and quantities. In addition to the no biofuel benchmark, in this section we consider three policy regimes: (1) a binding blend mandate, (2) a binding blender's tax credit, and (3) no biofuel policy.[3] The first two policy regimes correspond to biofuel policies historically used in the United States. The link between corn and ethanol prices when ethanol is produced is modeled as in de Gorter and Just (2008), Drabik (2011), and Mallory et al. (2012).

The No Biofuel Benchmark

In the absence of ethanol production,[4] the total U.S. corn supply, $S_C\left(P_C\right)$, at price P_C is used for (*i*) domestic food (e.g., corn syrup) and feed production (e.g., feed for hogs),

[3] In the empirical section, we also consider the combination of a binding mandate with a blender's tax credit. Because the qualitative results for this policy regime are the same as for the mandate alone, we do not elaborate on the combination of a mandate with the tax credit in this section.

[4] The term "no ethanol production" is not a synonym for "no ethanol policy". It is because under some conditions, specified in the section *No Biofuel Policy*, ethanol production can occur even without any biofuel policy.

collectively denoted by x, and (ii) exports, with the export demand curve facing the U.S. corn market denoted by $\bar{D}(P_C)$. The equilibrium in the corn market thus requires

(1) $$S_C(P_C, Z_1) = x + \bar{D}(P_C, Z_2)$$

where Z_i , i = {1, 2}, denotes an exogenous shifter of the corn supply curve (e.g., due to the 2011/12 drought in the United States) and of the foreign corn demand (e.g., higher incomes in the rest of the world), respectively. There are no shocks in the initial equilibrium, hence we set $Z_1 = Z_2 = 0$. A positive shock implies a rightward shift in a supply or a demand curve.

Domestic corn is processed by a competitive industry into food/feed according to a well-behaved production function $f(x)$, i.e., the function satisfies: $f(0) = 0$, $f_x > 0$, and $f_{xx} < 0$. The subscript denotes the derivative of the production function with respect to the argument.

Denoting $D_f(p)$ as the demand for food at price p and Z_3 as an exogenous food demand shifter (e.g., due to higher incomes or population growth), the equilibrium in the food market is given by

(2) $$D_f(p, Z_3) = f(x)$$

The first-order condition for profit maximization in the food processing industry implicitly defines the demand for corn

(3) $$pf_x = P_C$$

Totally differentiating the system of equations (1) through (3), we arrive at

(4) $$\begin{gathered} \left(S_{CP_C} - \bar{D}_{P_C}\right) dP_C + S_{CZ_1} dZ_1 = dx + \bar{D}_{Z_2} dZ_2 \\ D_{fp} dp + D_{fZ_3} dZ_3 = f_x dx \\ f_x dp + pf_{xx} dx = dP_C \end{gathered}$$

where the subscripts on the market supply and demand curves denote partial derivatives with respect to individual arguments. With the system of equations (4), we are in a position to derive price transmission elasticities in the absence of ethanol production pertaining to individual market shocks.

A shock in the corn supply of dZ_1 ($dZ_2 = dZ_3 = 0$) changes the corn price by dP_C/dZ_1 and the food price by dp/dZ_1. Following McCorriston et al. (2001), we calculate the price transmission elasticity, ε_{Z_1}, of a shock in the corn supply as[5]

(5) $$\varepsilon_{Z_1} = \frac{\Delta p}{\Delta P_C}\frac{P_C}{p} = \frac{dp/dZ_1}{dP_C/dZ_1}\frac{P_C}{p}$$

Setting $dZ_3 = 0$ in the second equation of the system (4), and solving the system for dp/dZ_1 obtains

(6) $$\frac{dp}{dZ_1} = \frac{f_x}{f_x^2 + pf_{xx}D_{fp}}\frac{dP_C}{dZ_1}$$

Substituting expression (6) into the formula (5), using the expression for the term f_{xx} derived in Appendix 1, invoking that $f_x = P_C/p$ (from equation (3)), and converting the price derivative D_{fp} into its elasticity form ($D_{fp} = \eta_f^D D_f/p$), we obtain

(7) $$\varepsilon_{Z_1}^{NB} = \frac{\eta_f^S}{\eta_f^S - \eta_f^D} \leq 1$$

Where η_f^S denotes a price elasticity of food supply (derived in Appendix 2), and η_f^D is a price elasticity of food demand.

Applying an analogous procedure, we obtain an identical expression for the price

[5] The change in the corn price is in the denominator because the primary effect of the corn supply shock is to affect the corn price, which in turn has an effect also on the food price.

transmission elasticity of a shock in the foreign corn export demand, ε_{Z_2}

(8) $$\varepsilon_{Z_2}^{NB} = \frac{dp/dZ_2}{dP_C/dZ_2}\frac{P_C}{p} = \frac{\eta_f^S}{\eta_f^S - \eta_f^D} \le 1$$

Intuitively, elasticities (7) and (8) are expected to be identical because the shock occurs in the same (corn) market and leads to the same corn price change. It should, however, be noted that the elasticity formulas in this theoretical section are derived using marginal analysis and therefore might differ from the empirical results, especially for non-marginal shocks.

The price transmission elasticity ε_{Z_3} relates to the price shock in the food market (due to a shift in the food demand curve), which causes a subsequent change in the corn price (see Appendix 3 for details)

(9) $$\varepsilon_{Z_3}^{NB} = \frac{dP_C/dZ_3}{dp/dZ_3}\frac{p}{P_C} = \frac{\eta_f^S}{\eta_f^S + \phi\eta_C^S - \rho\bar{\eta}_C^D} \le 1$$

where η_C^S and $\bar{\eta}_C^D$ denote elasticities of the corn supply and export demand curves, respectively, and $\phi = P_C S_C / pf$ and $\rho = P_C \bar{D}_C / pf$ denote the shares of the value of corn supply and corn exports, respectively, in the value of food production.

A close inspection of elasticities (7), (8), and (9) shows that the transmission elasticity stemming from a shock in the corn market can be smaller, equal, or greater than the elasticity of a food demand shock, depending on the relative supply and demand elasticities and value shares. For example, a shock in the corn market results in smaller transmission elasticity than the shock in the food market as long as $\eta_f^D \le \rho\bar{\eta}_C^D - \phi\eta_C^S$. Empirically, we find the transmission elasticities under no ethanol production (benchmark) to be equal to 0.84 and 0.61 for the corn and food market shocks, respectively (see further).

Binding Blend Mandate[6]

Under a binding blend mandate α, ethanol has to constitute at least α[x100] percent of the final fuel blend. The fuel (blend of ethanol and gasoline) price, P_F, is equal to the weighted average of the ethanol and gasoline prices, P_E and P_G, respectively, adjusted for the fuel tax, t, and the ethanol tax credit, t_c, (if any) (de Gorter and Just 2009b; Drabik 2011)

(10) $$P_F = \alpha\left(P_E + t/\lambda - t_c/\lambda\right) + \left(1-\alpha\right)\left(P_G + t\right)$$

The term $\lambda = 0.7$, denotes miles per gallon of ethanol relative to gasoline (de Gorter and Just 2008), and is used to consistently convert all prices and quantities into gasoline energy-equivalent terms (Cui et al. 2011; Lapan and Moschini 2012).

The zero marginal profit condition for ethanol production implies a link between corn and ethanol prices (de Gorter and Just 2008; Drabik 2011, Lapan and Moschini 2012)

(11) $$P_C = \frac{\lambda\beta}{1-r\gamma}\left(P_E - c_0\right)$$

where $\beta = 2.8$ denotes gallons of ethanol per bushel of corn (Eidman 2007); r denotes the relative price of Dried Distillers Grains with Solubles (DDGS)[7] and corn; $\gamma = 17/56$ is the share of DDGS per bushel of corn; and c_0 denotes (constant) processing cost per gasoline energy-equivalent gallon of ethanol.

The ethanol supply curve S_E is determined by the horizontal difference between corn supply and demand for corn for domestic food/feed use and corn exports

(12) $$S_E\left(P_E\right) \equiv \frac{\lambda\beta}{1-r\gamma}\left[S_C\left(P_C, Z_1\right) - x - \bar{D}\left(P_C, Z_2\right)\right]$$

[6] Although the U.S. Renewable Fuel Standard (RFS) stipulates a quantitative mandate for ethanol, in practice it is implemented as a blend mandate. Therefore, we do not analyze price transmission elasticities under a quantity mandate.

[7] DDGS, a valuable co-product of ethanol production, is returned into the corn market and is used for feeding animals. Drabik (2011) provides details on the economics of this co-product and further explanation of equation (12).

In the presence of ethanol production, the term x does not represent solely yellow corn (as it was the case in the previous section where ethanol was not produced) but rather the corn-equivalent quantity of corn and DDGS that is used in food production. This does not pose a problem for our analysis as we measure the food production and associated corn inputs in dollar terms. The dollar value makes it possible to accommodate a possibly separate use of DDGS (e.g., as a hog feed, where the pork is subsequently counted as food) and yellow corn (e.g., directly used for pop-corn) for food production.

For later use, we write the corn use identity as

$$S_C \equiv x + \bar{D} + S_C^E \tag{13}$$

where S_C^E denotes the amount of corn *initially*[8] allocated to ethanol production. Identity (13) can be converted into

$$\frac{P_C x}{pf} \equiv \phi - \rho - \mu \tag{14}$$

where $\mu = P_C S_C^E / pf$ denotes the share of the value of corn diverted to ethanol in the value of food production.

The equilibrium in the ethanol market requires that ethanol supply be equal to ethanol demand; the latter is proportional to the fuel demand

$$S_E(P_E) = \alpha D_F(P_F) \tag{15}$$

Total fuel demand has to also equal total fuel supply

$$D_F(P_F) = S_G(P_G) + S_E(P_E) \tag{16}$$

[8] We stress the word *initially* because this is not the final quantity of yellow corn used in ethanol production. It is because ethanol production yields DDGS as a co-product which is almost a perfect substitute for yellow corn for animal feed. Therefore, the yellow corn that DDGS replaces can be further used for ethanol production.

Total differentiation of equations (2), (3), (10), (11), (15), and (16) (with the substitution identity (12) into equations (15) and (16)), yields

$$
(17)\qquad
\begin{gathered}
D_{fp}dp + D_{fZ_3}dZ_3 = f_x dx \\
f_x dp + pf_{xx}dx = dP_C \\
dP_F = \alpha dP_E + \left(1-\alpha\right)dP_G \\
dP_C = kdP_E \\
\alpha D_{FP_F}dP_F = k\left(S_{CP_C} - \bar{D}_{P_C}\right)dP_C + kS_{CZ_1}dZ_1 - kdx - k\bar{D}_{Z_2}dZ_2 \\
D_{FP_F}dP_F = S_{GP_G}dP_G + k\left(S_{CP_C} - \bar{D}_{P_C}\right)dP_C + kS_{CZ_1}dZ_1 - kdx - k\bar{D}_{Z_2}dZ_2
\end{gathered}
$$

where we use a short-hand notation $k = \lambda\beta/\left(1-r\gamma\right)$, and the prime (') to denote the derivative with respect to a sole argument.

Because the first two equations in the system (17) are identical to the last two equations in system (4), it must be that the functional forms of the transmission elasticities with blend mandate (denoted by the superscript BM) related to the supply/foreign demand shocks in the corn market are the same

$$
(18)\qquad \varepsilon_{Z_1}^{BM} = \varepsilon_{Z_2}^{BM} = \frac{\eta_f^S}{\eta_f^S - \eta_f^D} \le 1
$$

The magnitudes of elasticities in (18) in general differ from their counterparts with no corn-ethanol linkage in (7) and (8). The reason is that both sets of elasticities pertain to different market equilibria.[9] However, the difference will be rather small and we expect almost equal elasticities with and without ethanol.

The price transmission elasticity for the shock in the food demand under the blend mandate takes the form (for derivation see Appendix 3)

[9] This point is explained in a greater detail in the section on data and calibration.

(19) $$\varepsilon_{Z_3}^{BM} = \frac{\eta_f^S}{\left(\eta_f^S + \phi\eta_C^S - \rho\bar{\eta}_C^D\right) - \frac{\alpha\mu}{\omega m}\eta_G^S\eta_F^D\frac{P_F}{P_G}} \leq 1$$

where $\omega = P_F S_E / P_C S_C^E$, and $m = \eta_G^S \frac{P_F}{P_G} - (1-\alpha)\eta_F^D$; η_G^S and η_F^D denote gasoline supply and fuel demand elasticities, respectively.

Formula (19) differs from formula (9) by a term which captures the parameters of the fuel market. Since the term is positive, the transmission elasticity for a food demand shock under a blend mandate should generally be smaller than the transmission elasticity with no biofuels. Note, however, that because the market equilibria corresponding to formulas (9) and (19) are not the same, the magnitudes of the (endogenous) terms ϕ and ρ differ between the formulas, making the two elasticities not exactly comparable. In fact, in Table 2 below we show that the transmission elasticity related to the food demand shock is empirically found to be slightly higher under the mandate relative to the no biofuel benchmark (see further).

Binding Blender's Tax credit

Because under a binding blender's tax credit, fuel consumers are not mandated to consume ethanol, they will only do so if the consumer price of ethanol, inclusive of the reduced tax due to the tax credit (t_c), is the same as the consumer price of gasoline, i.e., $P_G + t$ (de Gorter and Just 2008; Cui et al. 2011; Lapan and Moschini 2012). For the market price of ethanol, we then have

(20) $$P_E = P_G - \left(\frac{1}{\lambda} - 1\right)t + \frac{t_c}{\lambda}$$

And the consumer fuel price is given by

(21) $$P_F = P_G + t$$

Totally differentiating the system of equations (2), (3), (20), (21), (11), and (16) (with the substitution of equation (12) into (16)), which constitute the market equilibrium under a binding tax credit, we arrive at

$$
\begin{aligned}
D_{fp}dp + D_{fZ_3}dZ_3 &= f_x dx \\
f_x dp + pf_{xx}dx &= dP_C \\
dP_E &= dP_G \\
dP_F &= dP_G \\
dP_C &= kdP_E \\
D_{FP_F}dP_F &= S_{GP_G}dP_G + k\left(S_{CP_C} - \bar{D}_{P_C}\right)dP_C + kS_{CZ_1}dZ_1 - kdx - k\bar{D}_{Z_2}dZ_2
\end{aligned}
\tag{22}
$$

The first two equations in the system (22) are the same as the last two equations in (4), hence the expressions for the price transmission elasticity of shocks in the corn market must be the same as in the case of no biofuels and with a binding blend mandate

$$
\varepsilon_{Z_1}^{TC} = \varepsilon_{Z_2}^{TC} = \frac{\eta_f^S}{\eta_f^S - \eta_f^D} \leq 1 \tag{23}
$$

where the super script TC denotes the case of a tax credit.

The price transmission elasticity of a shock in the food demand under the tax credit is given by (for derivation see Appendix 3)

$$
\varepsilon_{Z_3}^{TC} = \frac{\eta_f^S}{\left(\eta_f^S + \phi\eta_C^S - \rho\bar{\eta}_C^D\right) + \dfrac{\mu}{\omega}\left(\theta\eta_G^S - \sigma\eta_F^D\right)} \leq 1 \tag{24}
$$

where $\theta = P_F S_G / P_G S_E$ and $\sigma = P_G D_F / P_G S_E$.

The last term in the denominator in equation (24), $\mu\left(\theta\eta_G^S - \sigma\eta_F^D\right)/\omega$, is unambiguously positive which implies that the price transmission elasticity with the binding tax credit should generally be smaller than the elasticity with no biofuel. For the extreme case of a perfectly elastic gasoline supply and/or fuel demand curve, the expression (24) reduces to zero, $\varepsilon_{Z_3}^{TC} = 0$. In this case, the corn price does not respond to food demand shocks; the corn price is directly linked to the exogenous gasoline price - through the ethanol price given in (20) - and is thus insensitive to any shock in the food market. This implies that the linkage between corn and ethanol markets makes the corn price less responsive to food price changes when the tax credit is binding.

No Biofuel Policy

Corn ethanol production can also take place without biofuel policy. This is possible in several cases. First, with increased corn productivity the availability of crop may expand, leading to lower feedstock prices thus making ethanol production profitable even in the absence of biofuel policy. Second, if gasoline prices are sufficiently high, then the free market ethanol price increases according to equation (20) (with the tax credit set to zero as is the case with no biofuel policy), thus potentially making ethanol production profitable. Third, a technological change can also result in ethanol production without a policy. Consider, for example, a decrease in the ethanol processing cost, c_o, due to lower natural gas prices. (Natural gas takes up the highest share of the corn ethanol processing cost). Then, as equation (11) indicates, the price of corn that the ethanol industry is willing to pay increases (because of higher probability of ethanol production) for a given ethanol price leading to free market ethanol production. A higher extraction rate for ethanol from corn, the term β in equation (11), and a higher price of DDGS relative to corn (the term r in the same equation) have a similar effect on the corn price.

In all cases above, the consumer is not mandated to consume ethanol and will do so only when the final price of ethanol per mile is lower than the final price of gasoline. Hence, this is the same case as for the tax credit (for $t_c = 0$). Therefore, the model set-up for the market equilibrium with the tax credit (set to zero) applies for the no biofuel policy case as well. Consequently, the formulas for price transmission elasticities are the same as well. The binding tax credit and the no biofuel policy scenarios differ in the size of the ethanol sector. With tax credit the ethanol sector is expected to be larger because the tax credit increases the ethanol prices, leading to higher ethanol production.

3. Data and Calibration

We calibrate the model to the data describing the U.S. corn, food, and fuel markets in 2009. The demand and supply curves exhibit constant price elasticity. We adopt some parameters and raw data from a well established paper by Cui et al. (2011) as their corn-ethanol model is also calibrated to the year 2009. We provide an explanation for cases when our data differ from theirs. A self explanatory documentation of the data used is presented in Appendix 5. All fuel price and quantity data are converted into gasoline energy-equivalents to consistently model the linkages in the fuel market.

Two principal corn ethanol policies were in place in the United States in 2009: the blender's tax credit and the blending (share) mandate. Because only one biofuel policy can determine the biofuel price at a time (de Gorter and Just 2009b), it is crucial to determine the binding policy in order to properly calibrate the model. Cui et al (2011) calibrate their model to the blender's tax credit arguing (in footnote 36) that "because ethanol production for 2009 exceeds the mandate level, […] the mandate does not bind, and […] it is the fuel tax and ethanol subsidy policies that affect equilibrium values". However, de Gorter and Just (2010) show that the comparison of the observed quantity of ethanol with the mandated level does not reliably determine which policy is binding and argue for comparing the observed ethanol market price with what the price would be if the tax credit were binding. de Gorter and Just (2010)'s empirical analysis shows that the binding policy in 2009 was the mandate.[10] Thus, we calibrate our model

[10] An indication that the blender's tax credit was not a binding policy in 2009 is the gasoline price. Cui et al. (2011) calculate it to be $2.11/gallon which is 35 cents more than the observed wholesale price of $1.76/gallon.

to a binding mandate combined with a tax credit; we refer to this model as the *baseline*.

The upper part of Appendix 5 presents parameters that describe the link between corn and ethanol prices and quantities; we also recognize that one gallon of corn ethanol yields only approximately 70 percent of the mileage compared to gasoline. The returns-to-scale parameter of the food production function is estimated to be $\varepsilon = 0.33$ which corresponds to the food supply elasticity of $\eta_f^S = 0.48$ (Appendix 4).

As explained above, the blend mandate of $\alpha = 5.7$ energy percent is the binding biofuel policy in our model. To be consistent with observed market data, we calculate the mandate as the share of the (energy) amount of ethanol in the (energy) amount of total fuel. In 2009, a corn ethanol blender's tax credit of $0.45/gallon and the (federal plus state average) gasoline tax of $0.39/gallon were also in place.

The gasoline and ethanol wholesale (rack) prices come from Omaha, Nebraska. The price of fuel (a blend of ethanol and gasoline) is equal to the weighted average of ethanol and gasoline prices adjusted for the fuel tax and the tax credit and amounts to $2.17 per gasoline energy-equivalent gallon (GEEG). Corn and ethanol prices are linked through a zero marginal profit condition for ethanol production. The price of food is normalized to unity which makes it possible to use the dollar value of the food production as the food quantity.

The U.S. ethanol production (equal to consumption in our model) in 2009 amounted to 10.76 billion gallons (corresponding to 7.53 billion GEEGs), and the total fuel (i.e., gasoline plus ethanol) consumption was 134.74 billion gallons. Therefore, the gasoline consumption equals 134.74 - 10.76 = 123.61 billion gallons, making the total fuel consumption in energy terms be equal to 131.14 GEEGs.

Corresponding to the 10.76 billion gallons of ethanol is 2.84 billion bushels of yellow corn; this estimate does, however, not take into account the amount of the ethanol co-product, DDGS (Dried Distillers Grains with Solubles) that is returned to the corn market. Taking the DDGS into consideration, the total quantity of yellow corn diverted to ethanol production is 3.84 billion bushels. The difference between 3.84 billion bushels and 2.84 billion bushels thus gives the amount DDGS placed on the market. Following Hoffman and Baker (2011), we assume 81 percent of DDGS is consumed domestically and the rest is exported.

The total yellow corn supply in the United States in 2009 was 13.15 billion bushels, of which 1.86 billion bushels were exported. We estimate the quantity of yellow corn used in food/feed as the residual after the export and ethanol markets have been satisfied, that is, 13.15 – 3.84 – 1.86 = 7.45 billion bushels. However, the total amount of corn equivalent used in the food/feed sector is equal to 7.45 + 0.81x1.00 = 8.26 billion bushels, reflecting that 81 percent of DDGS stayed in the domestic market in 2009. An analogous adjustment has been made for the corn-equivalent amount of exports.

We use the Annual Survey of Manufacturers (ASM) from the U.S. Census Bureau to estimate the value of food production that is related to corn.[11] The total value of food production (where corn is used) is $94.85 billion. The list of items included in this amount is presented in Table 1. Because more than 80 percent of U.S. corn ethanol plants are dry mills due to lower capital costs,[12] we do not include products of wet milling into the value of food production.

Demand and supply elasticities play an important role in our analysis. We use the central estimates for elasticities of corn supply, foreign corn import demand, and gasoline supply as reported in Cui et al. (2011); the lower and upper limits for the sensitivity analysis are also very similar (see the bottom part of Appendix 5) to Cui et al. (2011)'s. The elasticity of food/feed

[11] http://www.census.gov/manufacturing/asm/historical_data/index.html
[12] http://www.afdc.energy.gov/fuels/ethanol_production.html

corn demand is calculated as per equation (A4.6) and is equal to -0.23, which is very close to the value reported by Cui et al. (2011) (-0.20).

The elasticity of food demand comes from Seale et al. (2003) and is equal to -0.09, which is consistent with the empirical observation that demand for food is very inelastic. Central estimate of the fuel demand elasticity of -0.26 comes from Hamilton (2009), and the lower and upper limits reflect the low and upper estimates of the recent meta-analysis by Havránek et al. (2012).

4. Simulation Results

We use the baseline parameters to construct equilibria for the no biofuel benchmark and four policy regimes: (1) a binding mandate combined with a tax credit (the baseline), (2) a binding mandate alone, (3) a binding blender's tax credit, and (4) no biofuel policy.

In the benchmark and each regime, similar as in the theoretical section, we (separately) introduce exogenous shocks in corn supply, domestic and foreign corn demand, denoted as Z_1, Z_2, and Z_3, respectively, to calculate price transmission elasticities related to each shock. The magnitude of each shock is equal to 10 percent of the consumption/production corresponding to the no-shock case. Thus, for example, the (negative) corn supply shock under the binding tax credit regime is equal to 10 percent of the corn supply in the shock-free equilibrium for that policy regime. The price transmission elasticities are then calculated from the simulated changes in corn and food prices relative to the no-shock prices.

We perform a Monte Carlo analysis to check the robustness of our results to the exogenous elasticities. To that end, we vary elasticities of corn supply, foreign corn import demand, food demand, fuel demand, and gasoline supply. We make 5000 random draws for each of the elasticities from a beta distribution whose parameters are derived from the lower, central, and upper values of the elasticities specified in Appendix 5, using the PERT method (Davis 2008).

Price transmission elasticities

Table 2 presents a summary of results for the price transmission elasticities obtained from Monte Carlo simulations. We focus our discussion on the central estimates of the transmission elasticities (the heavy font). For corn market shocks (Z_1 and Z_2) in the no biofuel benchmark, the price transmission elasticity is 0.84, meaning that a 10 percent increase in the corn price causes an 8.4 percent increase in the price of food. On the other hand, for the food demand shock (Z_3) we estimate a smaller price transmission: a 10 percent increase in the price of food has corn prices increase only by 6.1 percent. The price transmission from the corn market to the food market is greater than the other way around because we consider larger elasticities of corn supply and export demand relative to the elasticity of food demand which causes smaller corn price responses than food price responses to a given shock (see Appendix 5 and equations (7), (8), and (9)).[13]

For the binding mandate (with or without the tax credit), the price transmission elasticities corresponding to individual shocks are very similar to the benchmark elasticities. To understand this stability, it is important to note that at the current mandate levels the ethanol market – the only link in our model between corn and food markets on the one hand and the gasoline market on the other – is small relative to the gasoline market. As a result, the simulated market shocks have a minimal impact on the fuel price which, in connection with inelastic fuel demand, implies minimal changes in the fuel consumption. Therefore, given the blend mandate – implemented as a fixed share of ethanol in the fuel consumption – the amounts of ethanol and

[13] From equations (7), (8), and (9) it follows that for a sufficiently low elasticity of corn supply and/or export demand (everything else held equal), the food-corn price transmission elasticity will equal or exceed the corn-food price transmission elasticity.

corn dedicated to ethanol production are not very sensitive to the market shocks. Under the binding mandate, the effects of the market shocks mostly materialize in the allocation of the residual amount of corn for non-ethanol uses. For example, the more the corn supply contracts (e.g., due to bad weather), the less corn is available for domestic food/feed use and for exports[14] but the amount of corn for ethanol does not change much.

Since for a given mandate the amount of ethanol does not response significantly to the market shocks, the corn price is effectively determined in the corn market.[15] In order to produce the mandated quantity of ethanol, ethanol producers need to pay for corn at least as much as the food sector is willing to pay. This mechanism of price formation under the mandate means that biofuels do not significantly affect the price transmission of shocks between corn and food prices. A change in the food (corn) price will be transmitted to the corn (food) price at the same rate both with the binding mandate and with no biofuels. This is documented by almost identical transmission elasticities in the first three columns in Table 2.

We observe a partially different result structure when the tax credit is binding (or when biofuels are produced without any biofuel policy). A significant effect of biofuels on price transmission along food chain occurs with the food demand shock, in which case the price transmission elasticity decreases significantly as compared to the no biofuel benchmark – a decrease from 0.61 to 0.35 (Table 2). The elasticities associated with the remaining shocks are largely the same as in the benchmark case.

With the binding tax credit (or no biofuel policy), consumers are not mandated to consume ethanol. They will only do so if the consumer price of ethanol, inclusive of the reduced

[14] The allocation between the two corn uses depends on relative demand elasticities of the food/feed and export demand curves.

[15] The corn price would be completely determined in the corn market if the mandate were implemented as a fixed quantity mandate.

tax due to the tax credit is lower than the consumer price of gasoline. This implies that under a binding tax credit the corn price is determined by the gasoline price (through the ethanol price) and not in the corn market as it was the case under the binding mandate. Consequently, a shock in the food market will affect the corn price only to the extent to which it can affect the gasoline price. Given the small size of the ethanol market relative to the gasoline market, the price transmission from the food to corn market is also small.

For a shock originating in the corn market, the price transmission is not affected by biofuels because, as explained earlier, biofuels do not affect the price linkages in the processing or food markets, hence any change in the corn price is transmitted to the food price at the same magnitude with or without biofuels.

In order to identify the effects of the exogenous model elasticities on the price transmission elasticities, we regress (separately for each shock and scenario) the transmission elasticities obtained from the 5000 simulations on corn supply, foreign corn import demand, food demand, fuel demand, and gasoline supply elasticities. To ease the interpretation of the results, the demand elasticities were converted into positive values in all regressions.

The results in Table 3 show that the food demand elasticity is by far the strongest determinant of price transmission elasticities for corn market shocks. The corn supply elasticity affects the transmission elasticities most in the case of the food market shock. For most shocks and scenarios, the price transmission elasticities increase with the elasticities of corn supply and foreign corn demand. The only exception is the food demand shock in which case the relationship is reversed (Table 3). This is because the formula for the price transmission elasticity for a food demand shock is the reciprocal of the formulas for other elasticities.

The sensitivity analysis for the fuel demand and the gasoline supply elasticities shows some heterogeneity across shocks and model scenarios. For each of the shocks, the price transmission elasticities do not respond statistically significantly to the changes in fuel demand/gasoline supply elasticities when the mandate is binding (Table 3). For all other cases, fuel demand/gasoline supply elasticities generally do significantly affect the magnitude of price transmission elasticities. This heterogeneity is due to the different ways – described above – through which the shocks are transmitted to and interact with the fuel market and corn market.

Price level changes

In addition to analyzing how biofuel policies affect the price transmission, which is a ratio of two relative measures, it is also important to investigate to what extent biofuels affect the price changes under various market shocks. To that end, in Table 4 we report a summary of percentage changes in food and corn prices for the benchmark and four policy regimes. We focus on the central estimates of these changes.

Corn ethanol's impact on the magnitude of the corn and food price responses to market shocks strongly depends on the biofuel policy. Compared to the no biofuel scenario, both food and corn price responses are not affected significantly when the mandate is binding. These results are similar to price transmission elasticities reported in Table 2 where biofuels did not affect price transmission when mandate was the binding policy.

However, when the tax credit is binding (or when the free market would support biofuel production), both food and corn price changes are lower relative to the no biofuel scenario for the corn and food market shocks Z_1, Z_2 and Z_3. This is in contrast to the price transmission elasticities reported in Table 2, where the transmission elasticity was reduced by biofuels only for the food price shock. The reason is that fuel market absorbs (through biofuels) the major share of corn price shocks. With the tax credit or in the absence of biofuel policies the corn price is determined by the gasoline price. Because ethanol's share in the total fuel is small, corn and/or food market shocks have a limited impact on the gasoline price, thus making the corn price responding little to the shocks. As derived in the theoretical analysis, in an extreme situation with a perfectly elastic gasoline supply or fuel demand curves, the corn price response to any corn or food market shocks is zero, implying that also the food price change is reduced significantly relative to the no biofuel situation.

5. Concluding remarks

The rise of the biofuel sector has created an important outlet for agricultural commodities. For example, biofuel production absorbs a significant amount of corn, sugarcane, wheat, sugar beet, and oilseeds. The increasing interdependence between the primary agricultural markets and energy markets may reduce the dependence of agricultural production on food markets, which in turn may reduce the price responsiveness along the whole agri-food chain. As a result, the income distributional effects of the agricultural support measures may change along the agri-food chain as well.

The results of this paper show that biofuels do affect the price transmission along the food chain but their effect depends on the biofuel policy and the type of an exogenous market shock. Compared to a situation of no biofuel production, biofuels reduce the price transmission elasticity when the blender's tax credit is binding. In this case, biofuels reduce the price transmission from food to corn but not *vice versa*. The corn price is more rigid when corn is linked to the fuel market through the tax credit because it is locked on to the gasoline price and thus can be affected to a lesser extent by shocks coming from food market. On the other hand, biofuels do not affect price formation in the food market; for this reason biofuels do not affect the price transmission from corn-to-food. Further, our results show that when the mandate is binding, biofuels do not impact the price transmission along the food chain.

A second impact of biofuels is on the magnitude of corn and food price responses to shocks occurring in the corn and food markets. Our results indicate that the response of corn and food prices to exogenous market shocks is smaller in the presence of biofuels, indicating that – in some situations – biofuels may reduce volatility in food markets. This will be the case when the tax credit is binding. In this case, most of the shock in the food market is absorbed by the fuel market because of the corn price's direct link to the gasoline price; thus, the volatility of corn and food prices is reduced due to biofuels. However, this does not hold when mandate is binding. The mandate directly determines the volume of the ethanol production and therefore also the amount of ethanol-dedicated corn. Any shock in the corn or food market is then absorbed by the residual corn and food markets and not by the fuel market. This is because corn dedicated for ethanol production is essentially fixed while the residual corn market remains exposed to market shocks at the same level as in the case of no biofuels. The shocks will be mainly reflected in changes in food production and corn supply for food, leading to corn and food price changes. Our results have important policy implications. The price transmission along the food chain recently attracted a lot of attention among policy makers (Areté 2012; European Commission 2009; Vavra and Goodwin 2005). It is often argued that the cause of low prices transmission from food to agricultural producer prices is market power of processing industry and/or supermarkets. The results of our paper indicate that the biofuels might be an additional cause of the reduced prices transmission in the food supply chain.

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Table 1. Products included in the value of food production using corn

Products and services code	Meaning of Products and services code		Sum of Products shipments value ($1,000)
3112117	Corn mill products		1830037
3112211	Corn sweeteners		6070174
3112214	Manufactured starch		2189667
3112218	Corn oil		992574
311611A	Pork, not canned or made into sausage, slaughtering plants		16379772
311611G	Pork, processed, not made into sausage, slaughtering plants		2137591
3116121	Pork, processed/cured, purchased carcasses		8296984
311615	Poultry processing		51150442
3119194	Corn chips and related products		5807472
		Total	94854713

Source: The Annual Survey of Manufactures (ASM), U.S. Census Bureau

Table 2. Price transmission elasticities (summary statistics for 5000 simulations)*

		No biofuel (benchmark)	Mandate & tax credit**	Mandate	Tax credit	No biofuel policy
Corn supply shock (Z_1)	Central	**0.84**	**0.83**	**0.83**	**0.84**	**0.84**
	Min	0.79	0.79	0.79	0.80	0.80
	Max	0.98	0.98	0.98	0.98	0.98
Corn export shock (Z_2)	Central	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**
	Min	0.80	0.80	0.80	0.80	0.80
	Max	0.98	0.98	0.98	0.98	0.98
Food demand shock (Z_3)	Central	**0.61**	**0.63**	**0.63**	**0.35**	**0.35**
	Min	0.49	0.53	0.53	0.27	0.27
	Max	0.74	0.80	0.80	0.45	0.45

Source: own calculations.
Note: * Standard deviation in each case is between 0.03 and 0.04. ** At the calibration point (baseline).

Table 3. The effect of model supply and demand elasticities on the price transmission elasticities

		Elasticity of corn supply	Elasticity of foreign corn import demand	Elasticity of food demand	Elasticity of fuel demand	Elasticity of gasoline supply
Corn supply shock (Z_1)	No biofuel (benchmark)	0.0103***	0.00248***	-1.572***	n.a.	n.a.
	Binding mandate and tax credit	0.0188***	0.00196***	-1.582***	-0.00038	-0.000187
	Binding mandate	0.0188***	0.00196***	-1.582***	-0.00038	-0.000188
	Binding tax credit	0.00221***	0.000231***	-1.544***	0.00457***	0.00497***
	No biofuel policy	0.00221***	0.000231***	-1.544***	0.00457***	0.00497***
Corn export shock (Z_2)	No biofuels (benchmark)	0.00322***	0.000404***	-1.530***	n.a.	n.a.
	Binding mandate and tax credit	0.00269***	0.000302***	-1.527***	-0.000343	-0.000157
	Binding mandate	0.00269***	0.000302***	-1.527***	-0.000343	-0.000157
	Binding tax credit	0.000517**	8.81E-06	-1.521***	0.000421	0.000632**
	No biofuel policy	0.000517**	8.81E-06	-1.521***	0.000421	0.000632**
Food demand shock (Z_3)	No biofuels (benchmark)	-0.325***	-0.0893***	0.234***	n.a.	n.a.
	Binding mandate and tax credit	-0.484***	-0.0439***	0.0598***	-0.00118	-0.000575
	Binding mandate	-0.484***	-0.0439***	0.0598***	-0.00121	-0.000558
	Binding tax credit	-0.131***	-0.0167***	0.00592***	-0.320***	-0.349***
	No biofuel policy	-0.131***	-0.0167***	0.00592***	-0.320***	-0.349***

Source: own calculations.

Notes: Coefficients are estimated by OLS regression. The demand elasticities were converted to positive values for an easier interpretation.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$; n.a. – not available

Table 4. Food and corn price changes due to market shocks under various policy regimes (%) (summary statistics for 5000 simulations)*

		No biofuel (benchmark)		Mandate & tax credit		Mandate		Tax credit		No biofuel policy	
		Food	Corn	Food	Corn	Food	Corn	Food	Corn	Food	Corn
Corn supply shock(Z_1)	Central	**10.6**	**12.7**	**13.6**	**16.3**	**13.6**	**16.3**	**4.6**	**5.4**	**4.6**	**5.4**
	Min	6.5	8.2	8.8	11.0	8.8	11.0	3.0	3.7	3.0	3.7
	Max	22.2	25.2	34.3	39.1	34.3	39.1	7.6	8.5	7.6	8.5
Corn export shock (Z_2)	Central	**2.6**	**3.1**	**2.0**	**2.3**	**2.0**	**2.3**	**0.7**	**0.8**	**0.7**	**0.8**
	Min	1.7	2.1	1.3	1.6	1.3	1.6	0.5	0.6	0.5	0.6
	Max	5.6	6.3	4.4	4.9	4.4	4.9	1.1	1.3	1.1	1.3
Food demand shock (Z_3)	Central	**46.4**	**28.2**	**48.4**	**30.3**	**48.4**	**30.3**	**28.2**	**9.7**	**28.2**	**9.7**
	Min	33.4	16.8	35.8	19.4	35.8	19.4	23.8	6.4	23.8	6.4
	Max	87.0	64.4	110.0	87.1	110.0	87.0	38.7	16.7	38.7	16.7

Source: own calculations

* Standard deviation in each case is between 0.1 and 8.3.

Appendices

Appendix 1. The Curvature of a Production Function and Elasticity of a Product Supply Curve

A competitive cost-minimizing food producer solves

$$\min_{\{x\}} C = P_C x,\ s.t. f\left(x\right) = q \tag{A1.1}$$

where the notation is explained in the text.

The properties of $f\left(\cdot\right)$, specified in the text, guarantee that it has an inverse, h, such that $f^{-1}\left(q\right) = h\left(q\right) = x$. The cost of production can thus be written as $C = P_C h\left(q\right)$. The food producer equalizes the marginal cost to the food market price

$$MC = dC/dq = P_C h_q = p \tag{A1.2}$$

Totally differentiating equation (A1.2) and rearranging, we obtain

$$dq/dp = 1/\left(P_C h_{qq}\right) \tag{A1.3}$$

By Inverse Function Theorem, we have

$$h_q\left(q\right) = 1/f_x\left(h\left(q\right)\right)$$

or more succinctly

$$h_q = 1/f_x \tag{A1.4}$$

Differentiating both sides of (A1.4) with respect to q and rearranging yields

$$h_{qq} = -f_{xx}/f_x^3 \tag{A1.5}$$

The supply elasticity of a product is defined as

$$\eta_f^S = \left(dq/dp\right)\left(p/q\right) \tag{A1.6}$$

Combining the relationships (A1.2) to (A1.6), we obtain

$$f_{xx} = -f_x^2/\eta_f^S f \tag{A1.7}$$

Appendix 2. Derivation of the Elasticity of the Food Supply Curve.

Totally differentiating the market clearing condition (2) for the food market, we obtain

$$f_x dx = D_{fp} dp \tag{A2.1}$$

Invoking $f_x = P_C / p$ and $D_{fp} = \eta_f^D D_f / p$, equation (A2.1) can be expressed as

$$dx/dp = \eta_f^D D_f / P_C \tag{A2.2}$$

which, after recognizing that in equilibrium $D_f = f$, can be rewritten to

$$\frac{dx}{dp}\frac{p}{x} = \eta_f^D \frac{pf}{P_C x} \tag{A2.3}$$

Totally differentiating equation (3) obtains

$$f_x dp + p f_{xx} dx = dP_C \tag{A2.4}$$

The substation of expression (A1.7) together with $f_x = P_C / p$ into (A2.4) after rearrangement produces

$$\frac{1}{\frac{dx}{dp}\frac{p}{x}} - \frac{1}{\eta_f^S}\frac{P_C x}{pf} = \frac{1}{\frac{dx}{dP_C}\frac{P_C}{x}} \tag{A2.5}$$

Substituting expressions (A2.3) and (14) into equation (A2.5) yields

$$(\phi - \rho - \mu)/\eta_f^D - (\phi - \rho - \mu)/\eta_f^S = 1/\eta_C^D \tag{A2.6}$$

where $\eta_C^D = \frac{dx}{dP_C}\frac{P_C}{x}$ is the price elasticity of the demand for corn of the food producer. The elasticity of the food supply, η_f^S, is then given by

$$\eta_f^S = \frac{\phi - \rho - \mu}{(\phi - \rho - \mu)/\eta_f^D - 1/\eta_C^D} \tag{A2.7}$$

Appendix 3. Price Transmission Elasticities for Shocks in Food Demand and Fuel Markets

No Ethanol Production

In this case, we only model the shock in the food demand. Solving the system of equations (4) for dP_C/dZ_3 and dp/dZ_3 results in

$$\begin{aligned}\frac{dP_C}{dZ_3} &= \frac{-f_x D_{fZ_3}}{D_{fp} - \left(S_{CP_C} - \bar{D}_{P_C}\right)\left(f_x^2 + pf_{xx} D_{fp}\right)} \\ \frac{dp}{dZ_3} &= \frac{-D_{fZ_3}\left[1 - pf_{xx}\left(S_{CP_C} - \bar{D}_{P_C}\right)\right]}{D_{fp} - \left(S_{CP_C} - \bar{D}_{P_C}\right)\left(f_x^2 + pf_{xx} D_{fp}\right)}\end{aligned} \tag{A3.1}$$

which after substitution into the price transmission elasticity formula (9) and conversion of derivatives into their elasticity forms produces the right-hand side expression in (9).

Binding Blend Mandate

Solving the system of equations (17) for dP_C/dZ_3 in terms of dp/dZ_3, we obtain

$$\frac{dP_C}{dZ_3} = \frac{\left(f_x^2 + pf_{xx} D_{fp}\right)}{f_x}\frac{dp}{dZ_3} + \frac{pf_{xx} D_{fZ_3}}{f_x} \tag{A3.2}$$

And the explicit expression for dp/dZ_3 is given by

$$\frac{dp}{dZ_3} = -\frac{B}{A} D_{fZ_3} \tag{A3.3}$$

where

$$\begin{aligned}A = &\left\{\left(f_x^2 + pf_{xx} D_{fp}\right)\left[\alpha^2 D_F' - k^2\left(S_{CP_C} - \bar{D}_{P_C}\right)\right] + k^2 D_{fp}\right\}\left[S_G' - (1-\alpha) D_F'\right] \\ &+ \alpha(1-\alpha) D_F'\left\{\left(f_x^2 + pf_{xx} D_{fp}\right)\left[\alpha D_F' - k^2\left(S_{CP_C} - \bar{D}_{P_C}\right)\right] + k^2 D_{fp}\right\}\end{aligned}$$

and

$$\begin{aligned}B = &\left\{pf_{xx}\left[\alpha^2 D_F' - k^2\left(S_{CP_C} - \bar{D}_{P_C}\right)\right] + k^2\right\}\left[S_G' - (1-\alpha) D_F'\right] \\ &+ \alpha(1-\alpha) D_F'\left\{pf_{xx}\left[\alpha D_F' - k^2\left(S_{CP_C} - \bar{D}_{P_C}\right)\right] + k^2\right\}\end{aligned}$$

Substituting derivatives (A3.2 and A3.3) to the general elasticity formula (9), and using the elasticity forms for the remaining derivatives, we obtain expression (19).

From the system of equations (17), for the shocks in the fuel demand, Z_4, and gasoline supply, Z_5, we obtain

$$\frac{dp}{dZ_4} = -\frac{\alpha k f_x S_{GP_G}}{A} D_{FZ_4} \qquad \frac{dp}{dZ_5} = \frac{\alpha(1-\alpha) k f_x D_{FP_F}}{A} S_{GZ_5}$$

and

$$\frac{dP_C}{dZ_4} = -\frac{\alpha k\left(f_x^2 + p f_{xx} D_{fp}\right) S_{GP_G}}{A} D_{FZ_4} \qquad \frac{dP_C}{dZ_5} = \frac{k\alpha(1-\alpha) D_{FP_F}\left(f_x^2 + p f_{xx} D_{fp}\right)}{A} S_{GZ_5}$$

Substituting these derivatives into the general price transmission elasticity formulas for shocks in the fuel market

$$\varepsilon_{Z_4}^{BM} = \frac{dp/dZ_4}{dP_C/dZ_4}\frac{P_C}{p} \text{ and } \varepsilon_{Z_5}^{BM} = \frac{dp/dZ_5}{dP_C/dZ_5}\frac{P_C}{p},$$

obtains expression (21).

Binding Tax Credit

The pairs of derivatives needed to calculate elasticities given by expressions (26) and (27) come from solving the system of equations (24):

$$\frac{dP_C}{dZ_3} = \frac{\left(f_x^2 + p f_{xx} D_{fp}\right)}{f_x}\frac{dp}{dZ_3} + \frac{p f_{xx}}{f_x} D_{fZ_3}$$

$$\frac{dp}{dZ_3} = -\frac{\left\{k^2\left[p f_{xx}\left(S_{CP_C} - \bar{D}_{P_C}\right) - 1\right] - p f_{xx}\left(D_F' - S_G'\right)\right\} D_{fZ_3}}{k^2\left[\left(f_x^2 + p f_{xx} D_{fp}\right)\left(S_{CP_C} - \bar{D}_{P_C}\right) - D_{fp}\right] - \left(f_x^2 + p f_{xx} D_{fp}\right)\left(D_F' - S_G'\right)}$$

$$\frac{dp}{dZ_4} = -\frac{k f_x}{C} D_{FZ_4} \qquad \frac{dp}{dZ_5} = \frac{k f_x}{C} S_{GZ_5}$$

and

$$\frac{dP_C}{dZ_4} = -\frac{k\left(f_x^2 + p f_{xx} D_{fp}\right)}{C} D_{FZ_4} \qquad \frac{dP_C}{dZ_5} = \frac{k\left(f_x^2 + p f_{xx} D_{fp}\right)}{C} S_{GZ_5}$$

where $C = \left[D_{FP_F} - S_{GP_G} - k^2\left(S_{CP_C} - \bar{D}_{P_C}\right)\right]\left(f_x^2 + p f_{xx} D_{fp}\right) + k^2 D_{fp}$

Appendix 4. Calibration of the Numerical Model

Our numerical models (for individual policies and scenarios) closely follow their counterparts specified in the theoretical part of the paper. We use a decreasing returns-to-scale food production function $f = Fx^{\varepsilon}$. The first-order condition for profit maximization in food production becomes

$$p\varepsilon Fx^{\varepsilon-1} = P_C \tag{A4.1}$$

Calculating the ratio $P_C x / pf$ produces

$$\frac{P_C x}{pf} = \frac{p\varepsilon Fx^{\varepsilon-1}x}{pFx^{\varepsilon}} = \varepsilon \tag{A4.2}$$

This means that the returns-to-scale parameter ε of the food production function can be directly estimated from the observed data as the ratio of the value of the corn processed into food/feed and the value of the food production.

The firm's cost minimization problem for the given production technology yields the link of the returns-to-scale parameter, ε, and the food supply elasticity, η_f^S

$$\varepsilon = \frac{\eta_f^S}{\eta_f^S + 1} \tag{A4.3}$$

Substituting first the left-hand side of (14) into (A2.7) and then substituting the resultant formula into (A4.3), and invoking that $f = Fx^{\varepsilon}$, we arrive at

$$\varepsilon = \frac{\dfrac{P_C}{pFx^{\varepsilon-1}}}{\dfrac{P_C}{pFx^{\varepsilon-1}}\left(1 + \dfrac{1}{\eta_f^D}\right) - \dfrac{1}{\eta_C^D}} \tag{A4.4}$$

From (A4.1), we have $F = P_C / p\varepsilon x^{\varepsilon-1}$. After substation of the parameter F into (A4.4) and some rearrangements, we obtain

$$\varepsilon = \left(1+\frac{1}{\eta_C^D}\right) \Bigg/ \left(1+\frac{1}{\eta_f^D}\right) \tag{A4.5}$$

from which we can finally express the elasticity of demand for corn for food/food as

$$\eta_C^D = \frac{1}{\varepsilon\left(1+\frac{1}{\eta_f^D}\right)-1} \tag{A4.6}$$

Appendix 5. Data Sources (2009)

Variable/parameter	Symbol	Value	Unit	Source
PARAMETERS				
Miles per gallon of ethanol relative to gasoline	λ	0.70		de Gorter and Just (2009a)
Ethanol produced from one bushel of corn	β	2.80	gallon/bushel	Eidman (2007)
DDGS production coefficient	γ	17/56		Eidman (2007)
DDGS relative price to corn	r	0.86		$r = (P_{DDGS}*56)/(P_C*2000)$
Price and quantity link between corn and ethanol market	k	2.65	GEEG/bushel	$k = \lambda\beta/(1-r\gamma)$
Ethanol processing cost	c_0	1.14	\$/GEEG	$c_0 = P_E - P_C/k$
Returns to scale parameter of the food production function	ε	0.33		$\varepsilon = P_C x / pf$
Share of domestic consumption of DDGS	ω	0.81		Hoffman and Baker (2011)
Value of corn supply in value of food production	ϕ	0.52		$\phi = P_C S_C / pf$
Value of corn equivalent exports in value of food prod.	ρ	0.08		$\rho = P_C \bar{D}_C / pf$
Value of (initial) corn used in ethanol in value of food production	μ	0.11		$\mu = P_C S_C^E / pf$
POLICY VARIABLES				
Blend mandate [a]	α	0.06		$\alpha = E/F$
Ethanol tax credit	t_c	0.45	\$/gallon	RFS2 [b]
Fuel tax	t	0.39	\$/gallon	Cui et al. (2011)
PRICES				
Gasoline price	P_G	1.76	\$/gallon	Gasoline average rack price in Omaha, Nebraska [c]
Ethanol market price (volumetric)	P_e	1.79	\$/gallon	Ethanol average rack price in Omaha, Nebraska [c]
Ethanol market price (energy)	P_E	2.56	\$/GEEG	$P_E = P_e/\lambda$
Fuel price	P_F	2.17	\$/GEEG	equation (10)
Food price	p	1.00		normalized
Corn market price	P_C	3.74	\$/bushel	Cui et al. (2011)
DDGS price	P_{DDGS}	114.38	\$/ton [d]	Cui et al. (2011)

Appendix 5. (continued)

Variable/parameter	Symbol	Value	Unit	Source
QUANTITIES				
Fuel demand (volume)	$\tilde{F}$	134.37	billion gallons	Cui et al. (2011)
Fuel demand (energy)	F	131.14	billion GEEGs	F = G + E
Ethanol consumption (volume)	e	10.76	billion gallons	Cui et al. (2011)
Ethanol consumption (energy)	E	7.53	billion GEEGs	$E = \lambda e$
Gasoline supply	G	123.61	billion gallons	$G = \tilde{F} - e$
Corn supply	S_C	13.15	billion bushels	Cui et al. (2011)
Consumption of yellow for food/feed	$\tilde{x}$	7.45	billion bushels	$\tilde{x} = S_c - \tilde{S}_C^E - \tilde{D}$
Consumption of corn-equivalent for food/feed	x	8.26	billion bushels	$x = \tilde{x} + DDGS^H$
Foreign yellow corn import demand	$\tilde{D}$	1.86	billion bushels	Cui et al. (2011)
Foreign corn equivalent import demand	$\bar{D}$	2.05	billion bushels	$\bar{D} = \tilde{D} + DDGS^F$
Corn used in ethanol production (initial) [e]	S_C^E	2.84	billion bushels	$S_C^E = E/k$
Corn used in ethanol production (equilibrium) [f]	$\tilde{S}_C^E$	3.84	billion bushels	$\tilde{S}_C^E = S_C^E/(1-r\gamma)$
DDGS supply	DDGS	1.00	billion bushels	$DDGS = r\gamma\tilde{S}_C^E$
Domestic DDGS consumption	$DDGS^H$	0.81	billion bushels	$DDGS^H = \omega * DDGS$
DDGS exports	$DDGS^F$	0.19	billion bushels	$DDGS^F = (1-\omega) * DDGS$
Food production	f	94.85	billion dollars	The Annual Survey of Manufactures (ASM), U.S. Census Bureau [g]
ELASTICITIES		central	(low, high)	
Elasticity of corn supply	η_C^S	0.30	(0.00, 0.50)	Cui et al. (2011)
Elasticity of food/feed corn demand	η_C^D	-0.23	(-0.29, 0.00)	equation (A4.6)
Elasticity of foreign corn import demand	$\eta_C^{\bar{D}}$	-1.50	(-3.00, -1.00)	Cui et al. (2011)
Elasticity of food demand	η_f^D	-0.09	(-0.12, 0.00)	Seale et al. (2003)
Elasticity of fuel demand	η_F^D	-0.26	(-0.31, -0.09)	Hamilton (2009)
Elasticity of gasoline supply	η_G^S	0.20	(0.10, 0.50)	Cui et al. (2011)

Notes:
[a] The blend mandate is expressed in energy terms.
[b] Renewable fuel standard
[c] http://www.neo.ne.gov/statshtml/66.html
[d] Short ton (= 2000 lbs)
[e] This quantity of corn does take into account the market effects of DDGS.
[f] This quantity of corn takes into account the market effects of DDGS.
[g] http://www.census.gov/manufacturing/asm/historical_data/index.html